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Resolving mass flux at high spatial and temporal resolution using GRACE intersatellite measurements

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[1] The GRACE mission is designed to monitor mass flux on the Earth's surface at one month and high spatial resolution through the estimation of monthly gravity fields. Although this approach has been largely successful, information at submonthly time scales can be lost or even aliased through the estimation of static monthly parameters. Through an analysis of the GRACE data residuals, we show that the fundamental temporal and spatial resolution of the GRACE data is 10 days and 400 km. We present an approach similar in concept to altimetric methods that recovers submonthly mass flux at a high spatial resolution. Using $4^\circ \times 4^\circ$ blocks at 10-day intervals, we estimate the mass of surplus or deficit water over a $52^\circ \times 60^\circ$ grid centered on the Amazon basin for July 2003. We demonstrate that the recovered signals are coherent and correlate well with the expected hydrological signal. **Citation:** Rowlands, D. D., S. B. Luthcke, S. M. Klosko, F. G. R. Lemoine, D. S. Chinn, J. J. McCarthy, C. M. Cox, and O. B. Anderson (2005), Resolving mass flux at high spatial and temporal resolution using GRACE intersatellite measurements, *Geophys. Res. Lett.*, *32*, L04310, doi:10.1029/2004GL021908.

1. Introduction

[2] The Gravity Recovery and Climate Experiment (GRACE) Mission is dedicated to providing an improved understanding of the Earth's gravity field both as a uniform mean field with better than 2° resolution, along with highly resolved estimates of the global mass flux about the mean field on a monthly basis [*Wahr et al.*, 2004; *Tapley et al.*, 2004a]. Models produced to date from GRACE are at least an order of magnitude better than any former modeling effort [e.g., *Lemoine et al.*, 1998]. The GRACE measurement system includes a highly accurate K band range-rate measurement (KBRR) made between two co-orbiting satellites separated by approximately 250 km. The intersatellite line-of-sight measurement precision delivered by GRACE is well below 1 μ/s, giving GRACE unique sensitivity to the accelerations induced on low Earth orbiting satellites.

[3] Currently, a major thrust of time-variable gravity (TVG) recovery from GRACE is focused on monthly gravity recovery through global spherical harmonic solutions [*Tapley et al.*, 2004a]. Although this has been largely successful, this approach has not exploited the fundamental resolution of the observations. In Section (3) we give evidence that the fundamental resolution of the observations is close to 400 km and 10 days. We offer a method for local TVG recovery through mass concentration blocks (mascons) which yields submonthly resolution while preserving high spatial resolution. This method also falls short of exploiting the fundamental resolution of GRACE. However it does provide a means for obtaining regional solutions which have a higher resolution, especially temporally, than what is currently provided by global spherical harmonic solutions.

[4] Solutions for TVG from GRACE that are based on block parameters enjoy some advantages that are either difficult or impossible to exploit in global spherical harmonic solutions. Parameters describing the mean value of a gravity parameter in a block over an interval of time easily lend themselves to a type of least squares neighbor constraint. This type of constraint causes pairs of parameters which describe the same phenomenon but at different times to stay close in value and enables improved temporal resolution [e.g., *Luthcke et al.*, 2003]. In Section (3) we show that these constraints permit solutions every 10 days. With the estimation of parameters at ten day intervals it is possible to avoid some types of temporal and spatial aliasing which are described in *Thompson et al.* [2004] and *Han et al.* [2004]. Application of this type of constraint is not so straightforward for solutions that do not use blocks. The current GRACE project solutions use a posteriori filters and averaging kernels [*Wahr et al.*, 2004] which are applied externally and do not participate in the least squares process.

[5] It is easy to demonstrate by the same analytical method described in *Ray et al.* [2003] that the signature in GRACE KBRR observations associated with each mass concentration manifests itself directly over the area of surplus or deficit mass. Because of this relationship it is possible to make mascon solutions using only the data which overfly a region of interest. This, combined with the use of GRACE short arc analysis techniques [*Rowlands et al.*, 2002] ensures that modeling problems (for example from ocean tides and other ocean effects) from one area can not affect the solution in another area. This can be a real problem in global solutions. In global solutions mismodeling in one area is propagated globally by aliasing through once per revolution effects in the orbit solution. For example, the aliasing effects deep inside continents arising from ocean tide errors can be seen in *Ray et al.* [2003]. The signal-mascon relationship has still one more advantage. Certain types of observation corrections that scale directly into mass over an area can be applied equally well before or after a solution has been made. Solutions do not need to be remade as new corrections become available.

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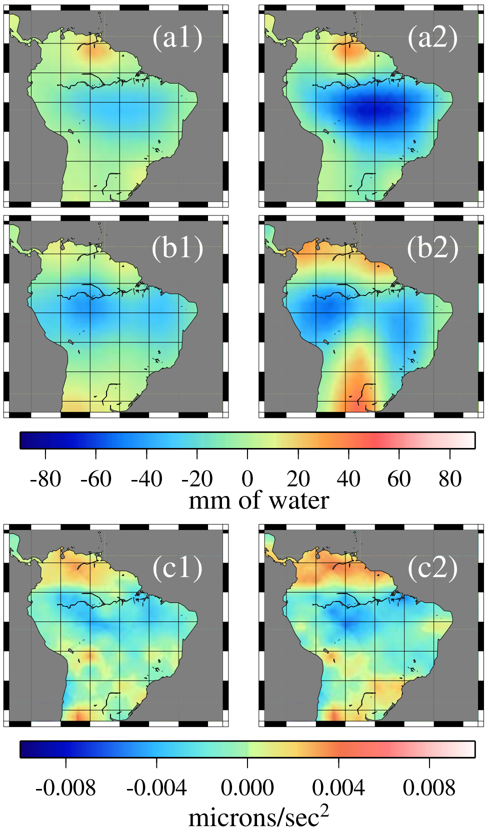

Figure 1. Each row gives a representation of change. The first two rows (panels a1, a2, b1, b2) show mass change (mm of water) from the hydrology model of *Rodell et al.* [2004] and our 10-day mascon solutions respectively. The last row (panels c1 and c2) show the change in the KBRR-dot residuals (μ/s^2). In column 1 (a1, b1, c1) the change is shown between two 10-day periods centered 10 days apart (July 6 and July 16, 2003). In column 2, the change is shown between two 10-day periods centered 20 days apart (July 6 and July 26, 2003). The region shown is from 274° to 332° East longitude and from 17°N to 35°S latitude.

[6] Some of the advantages of mascon parameters will be demonstrated in Section (3) where we will show a regional solution for mascons and compare that solution to global spherical harmonic solutions. Before that, in Section (2), we will give an explicit formulation for the recovery of mascons.

2. Mascon Parameters

[7] The formulation for mascon parameters exploits the fact that a change in potential caused by adding a small uniform layer of mass over a region at an epoch, t, can be represented as a set of (differential) potential coefficients which can be added to the mean background field. The delta coefficients can be computed as by *Chao et al.* [1987]:

$$\Delta A_{lm} = \frac{(1+k_l')R^2\sigma(t)}{(2l+1)M}\int Y_{lm}(\Omega)d\Omega \qquad (1)$$

where l and m are the spherical harmonic degree, k'_l is the loading Love number of degree l; R is the mean Earth radius; M is the mass of the Earth; Ω is a representation of surface area, and Y_{lm} is the spherical harmonic of degree l and order m corresponding to the potential coefficient A_{lm} and σ (t) is the mass of the layer over a unit of surface area at the epoch t.

[8] Each of our mascon parameters corresponds to a small block (4° × 4° in size for this analysis). For each block we use equation (1) to generate a set of "differential" Stokes coefficients that correspond to 1 cm of water over the block. The estimated mascon parameter for each block is a simple scale factor on the set of differential Stokes coefficients for that block. The partial derivative of the tracking observation with respect to a mascon parameter is just a linear combination of the partials of the tracking measurements with respect to standard Stokes coefficients. The multipliers are the Stokes coefficients in the base set of differential coefficients.

[9] Below we describe solutions for mascon parameters over a region centered on the Amazon basin using only tracking data that overflew this region. When only over-flight data are used there is the possibility of limiting the recovery of longer wavelength signal. This problem should be the greatest at the edge of the region. We mitigated the problem by estimating mascons over a region larger than our actual area of interest and discarding the results obtained at the edges.

3. Mascon Solutions

[10] The most important design consideration associated with a mascon solution is the base resolution chosen for the parameters, i.e., the length of time and the size of each parameter must be selected. Other considerations include the location, the central epoch and the duration of the solution. The design of our solution was guided by the analysis of GRACE KBRR observations from the time period July–October, 2003. We looked at the observations in the form of residuals computed by our orbit software, GEODYN. Residuals are observations with modeled signals (nonconservative forces, mean gravity, tides, etc) removed. We found it useful to look at differences of subsequent KBRR residuals which we call "KBRRdot residuals". In analytical simulations, the KBRRdot residuals strongly resemble the mascons they overfly to within a scale factor.

[11] In deciding on our mascon grid, we looked at various gridding schemes for making bins of KBRRdot residuals. As long as the bins in time and space are large enough, a coherent moving picture can be seen. The picture is coherent using bins of 400 km and 10 days, but becomes less clear when smaller bins are used. Based on analytical simulations it is almost certainly mass flux which is being depicted in these moving pictures. Furthermore, the drying of the Amazon over July–October, 2003 is clearly seen as well as the effects of monsoons in India. There is continuity across features in the 10-day intervals. Figure 1 shows that the change in features across ten day intervals agrees well with the change predicted by the hydrology model of *Rodell et al.* [2004].

[12] The solution described in this paper estimated mascons in 195 4° × 4° blocks over a 52° × 60° region centered on the Amazon basin. Each block was estimated every 10 days during the month of July 2003. This results in the estimation of 585 parameters. These parameters are estimated at the edge of their resolution and the solution

would be unstable without use of spatial and temporal constraints. Both types of constraints are accomplished by writing one constraint equation for each of the 170,820 distinct pairs of mascons in the solution. The constraint equation "forces" a pair (i,j) of mascons to stay close in value to each other. The weight given to the constraint is given by equation (2) and depends on the proximity of the pair in time and space:

$$\exp\left[2 - \frac{d_{ij}}{D} - \frac{|t_{ij}|}{T}\right] \tag{2}$$

where T and D are the correlation time and distance employed to form the constraint, d_{ij} is the distance between blocks i and j, and t_{ij} is the difference in time tags for blocks i and j. For 10-day mascon solutions we used a correlation time of 10 days and a correlation distance of 250 km. For thirty day mascon solutions, the correlation distance can be decreased to 175 km.

[13] Figure 1 gives a pictorial comparison between the hydrology assimilation model of *Rodell et al.* [2004], our mascon solutions and the KBRRdot residuals for July 2003. The comparison is given in the form of a difference of mass after 10 days and 20 days with respect to the first 10 days in July to show mass flux (and the underlying progression of regional hydrological change). By taking differences w.r.t. the first 10-day interval, we also eliminate errors in the mean mass distribution implied by the background gravity model, GGM01C [*Tapley et al.*, 2004b] and that of the mean hydrology model. There is good general agreement between the mass flux indicated by the hydrology and by the mascons, especially in the ten day differences. The twenty day differences also show generally the same trends, for example, continued accumulation of mass in the north and removal of mass at the latitude of the Amazon River system. In the south there is an accumulation of mass not indicated by the hydrology, which is seen by the mascons. The third row of Figure 1 shows that this accumulation is generally seen in the data. It should be pointed out that the mass flux indicated by the mascon solution for the twenty day difference is not entirely a continuation of the trend seen in the 10-day difference. The implication is that the changes in mascons indicate flux details that cannot be interpolated or extrapolated from monthly solutions.

[14] We then assessed whether the mascon parameterization permits the recovery of anything that would not be recovered by a global spherical harmonic solution, and if so, to what improved temporal and spatial resolution. We have generated our own spherical solutions to study this question. Our global spherical harmonic solution for the month of July 2003 compares well with the UT/CSR (University of Texas, Center for Space Research) Level 2 product from the GRACE project. Over the Amazon basin the two solutions show very similar features at the same spherical harmonic degrees. When we tried to make distinct global spherical solutions over 10 day intervals, however, we saw a marked degradation of the results as compared to the mascons. The ease with which mascons lend themselves to constraints permits submonthly solutions.

[15] The use of constraints does complicate the issue of quantifying the resolution that we obtain. The results of Figure 1 would indicate we obtain submonthly temporal resolution. Figure 2 is an attempt to put a bound on the spatial resolution achieved by our mascon solutions. It compares three monthly solutions over the Amazon. The first two solutions used a mascon parameterization while the third is the GRACE project (CSR) solution truncated at degree 13 (1500 km resolution). Since monthly (as opposed to 10-day) mascon recoveries do not require as much constraint as only one third the number of mascons are estimated, we found that a correlation distance of 175 km suffices. The second mascon solution uses the same correlation distance (250 km) as our 10-day mascons and is therefore over-constrained. The first mascon solution which is not as constrained, reveals significantly more detail than the second mascon solution. All three solutions show a high just south of the Amazon, although the high in both mascon solutions has a more complex shape. In both mascon solutions, meaningful variation is seen block to block, and this signal is accentuated in the first, less constrained, solution. While true 400 km resolution is not obtained, these block to block changes are not evident in the smooth spherical harmonic recovery.

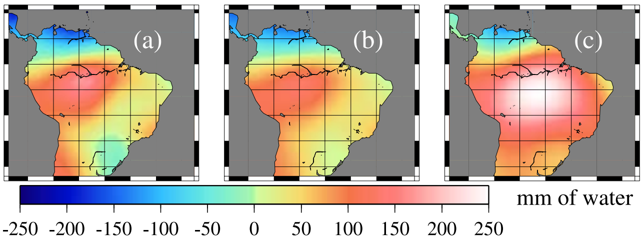

Figure 2. Each panel shows the difference in mass (mm of water) implied by a monthly solution for July 2003 and the mean gravity field GGM01C [*Tapley et al.*, 2004b]. Panels (a) and (b) use monthly mascon solutions with correlation distances of 175 km and 250 km respectively. Panel (c) is the GRACE project solution truncated to degree 13. The region shown is from 274° to 332° East longitude and from 17°N to 35°S latitude.

[16] The truncation at degree 13 for the comparison in Figure 2 was chosen for two reasons. The Amazon overflight data for July 2003 are fit best when the monthly spherical solution is used to replace coefficients of the a priori field (GGM01C) only through degree 13. This is true for our field as well as the GRACE project field. The higher degrees are evidently minimizing residuals over regions where forward models are problematic. Secondly, mass plots derived from both July 2003 solutions show evidence of streaking when truncated higher than degree 13. In support of this conclusion, many investigators, for example *Wahr et al.* [2004], have found it necessary to apply (a posteriori) smoothing of 1000 to 1500 km in order to isolate realistic mass flux signals from monthly spherical solutions. By truncating at degree 13 we use the best monthly spherical solution for the Amazon. It should also be noted that the monthly mascon solution fits the overflight data at 0.406 μ/s while the monthly spherical solutions (truncated to degree 13) fit at least 0.01 μ/s higher.

4. Conclusion

[17] We have found that GRACE measurements contain coherent mass flux signal at a resolution of 10 days and

400 km. Our local mascon approach was implemented to exploit these data to their limit of spatial and temporal resolution. Our approach also reduces known aliasing problems seen in standard Stokes monthly solutions whose static character further results in a loss of significant flux signal, especially in temporal resolution. Although we have not fully exploited the spatial resolution of these data, we resolve genuine submonthly temporal and detailed spatial effects. The formal error estimates for the submonthly mascon blocks range from ±1–2 mm of water with condition numbers being nearly equal to 1. Therefore, we have achieved a highly stable solution with excellent formal statistics through application of spatial and temporal constraints. The post-solution RMS of fit to the KBRR data obtained is 0.3–0.4 μ/s which reflects how well these mascons accommodate the KBRR signal. Systematic errors, largely dominated by errors in the forward models (i.e., tides, atmospheric pressure) and unresolved instrument calibrations are not reflected in these formal statistics and are error sources difficult to estimate without better characterization of these errors themselves. Additional parametric variations including tests using different forward models and empirical instrument correction strategies will be required for improved mascon error estimates.

5. Auxiliary Material

[18] We present three movies as auxiliary materials, to illustrate that the KBRR-dot residuals can be interpreted as a proxy for mass flux.[1] These include: (1) global ten-day snapshots of the KBRR-dot residuals from July to October 2003; (2) ten-day snapshots of the KBRR-dot residuals from July to October 2003 centered on the Amazon Basin; and (3) global ten-day snapshots of the surface hydrology from the model of *Rodell et al.* [2004]. The units on the KBRR-dot residuals are μ/s^2. The units on the hydrology map is mm of water. The mean from July to October 2003 was removed before creating the snapshots at ten-day intervals.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL021908.

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References

Chao, B. F., W. P. O'Connor, A. T. C. Chang, D. K. Hall, and J. L. Foster (1987), Snow load effects on the Earth's rotation and gravitational field, 1979–1985, *J. Geophys. Res.*, *92*(B9), 9415–9422.

Han, S.-C., C. Jekeli, and C. K. Shum (2004), Time-variable aliasing effects of ocean tides, atmosphere, and continental water mass on monthly mean GRACE gravity field, *J. Geophys. Res.*, *109*, B04403, doi:10.1029/2003JB002501.

Lemoine, F. G., et al. (1998), The development of the joint NASA GSFC and National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96, *NASA Tech. Pap., TP-1998-206861*.

Luthcke, S. B., N. P. Zelensky, D. D. Rowlands, F. G. Lemoine, and T. A. Williams (2003), The 1-centimeter orbit: Jason-1 precision orbit determination using GPS, SLR, DORIS and altimeter data, *Mar. Geod.*, *26*(3–4), 399–421.

Ray, R. D., D. D. Rowlands, and G. D. Egbert (2003), Tide models in a new era of satellite gravimetry, *Space Sci. Rev.*, *108*, 271–282.

Rodell, M., et al. (2004), The global land data assimilation system, *Bull. Am. Meteorol. Soc.*, *85*(3), 381–394.

Rowlands, D. D., R. D. Ray, D. S. Chinn, and F. G. Lemoine (2002), Short-arc analysis of intersatellite tracking data in a mapping mission, *J. Geod.*, *76*(6–7), 307–316, doi:10.1007/s00190-002-0255-8.

Tapley, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins (2004a), GRACE measurements of mass variability in the Earth system, *Science*, *305*(5683), doi:10.1126/science.1099192.

Tapley, B. D., S. Bettadpur, M. Watkins, and C. Reigber (2004b), The gravity recovery and climate experiment: Mission overview and early results, *Geophys. Res. Lett.*, *31*, L09607, doi:10.1029/2004GL019920.

Thompson, P. F., S. V. Bettadpur, and B. D. Tapley (2004), Impact of short period, non-tidal, temporal mass variability on GRACE gravity estimates, *Geophys. Res. Lett.*, *31*, L06619, doi:10.1029/2003GL019285.

Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna (2004), Time-variable gravity from GRACE: First results, *Geophys. Res. Lett.*, *31*, L11501, doi:10.1029/2004GL019779.

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